NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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AN EXPLORATORY INVESTIGATION OF SKIN FRICTION AND TRANSITION ON THREE BODIES OF REVOLUTION AT A MACH NUMBER OF 1.61

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SUMMARY

Skin-friction measurements were made for three bodies of revolution of fineness ratio 12.2 having different shapes and pressure distributions: an ogive-cylinder, a cone-cylinder, and a parabolic body. Tests were made at zero angle of attack and over a Reynolds number range, based on body length, from about 2.5×10^6 to 37×10^6.

The results were analyzed to determine the transition Reynolds numbers corresponding to the occurrence of transition at various longitudinal stations, that is, in regions having different pressure gradients. The results indicated marked differences in the transition Reynolds numbers for the three bodies of revolution and, in general, the effects of pressure gradient at a Mach number of 1.61 were qualitatively similar to those obtained at subsonic speeds. For transition at the body base, the highest transition Reynolds numbers are obtained with a long run of moderate, favorable pressure gradient followed by little or no adverse pressure gradient (parabolic body) rather than with a short run of very strong, favorable pressure gradient near the model nose followed by a long run of adverse pressure gradient. When transition occurred on the forward part of the body near the downstream end of the region of favorable pressure gradient, the transition Reynolds number was highest for the ogive-cylinder and cone-cylinder bodies which had the strongest favorable gradients. The results also indicate that, for a turbulent boundary layer, pressure gradients have little or no effect on the average skin-friction coefficients for the types of bodies investigated.

INTRODUCTION

Knowledge of boundary-layer transition is of primary importance in determining the skin friction and heat-transfer characteristics of airplanes or missiles at supersonic speeds. At the present time there is little information concerning transition at supersonic speeds, particularly regarding the effects of pressure gradients.

This paper presents the results of an exploratory investigation made in the Langley 4- by 4-foot supersonic pressure tunnel at a Mach number of 1.61 to determine the skin friction and boundary-layer transition Reynolds numbers for three bodies of revolution having different types of pressure distribution. The bodies investigated were an ogive-cylinder, a cone-cylinder, and a blunt-base parabolic (NACA RM-10) body. Tests were restricted to an angle of attack of zero and were made over a Reynolds number range, based on body length, from about 2.5×10^6 to 37×10^6.

SYMBOLS

α	angle of attack
C_f	average skin-friction coefficient based on wetted-surface area
L	model length
M	free-stream Mach number
P	pressure coefficient, $\frac{p_l - p}{q}$
p	free-stream static pressure
p_l	local static pressure
q	free-stream dynamic pressure
R	Reynolds number based on model length and free-stream conditions
R_T	transition Reynolds number based on model length and free-stream conditions
T_e	equilibrium surface temperature of model without heat transfer, $^{\circ}$F abs
T_l	local temperature just outside boundary layer, $^{\circ}$F abs
T_o	stagnation temperature, $^{\circ}$F abs
x	distance along model axis

APPARATUS AND METHODS

Wind Tunnel

The tests were conducted in the Langley 4- by 4-foot supersonic pressure tunnel which is a rectangular, closed-throat, single-return wind tunnel which has provisions for the control of the pressure, temperature, and humidity of the enclosed air. The test-section Mach number is varied by deflecting the top and bottom walls of the supersonic nozzle against fixed but interchangeable templates. The nominal Mach number range of the tunnel is from 1.2 to 2.2 with a stagnation-pressure range of $\frac{1}{8}$ to $2\frac{1}{4}$ atmospheres.

For the tests reported herein, the nozzle walls were set for a Mach number of 1.61. At this Mach number, the test section has a width of 4.5 feet and a height of 4.4 feet. Calibrations of the flow in the test section indicate that the Mach number variation is about ±0.01 and that there are no significant irregularities in the stream flow direction. The turbulence level in the test section is not known, but it is always less than 0.9 percent of the local velocity in the subsonic flow upstream of the first minimum where the local velocity is about 155 fps (ref. 1).

Models

An ogive-cylinder body of revolution having a 3-caliber nose and a cone-cylinder body with a $2\frac{1}{2}$- caliber nose were tested during this investigation. A sketch showing pertinent dimensions, mounting, and construction details of the ogive-cylinder and cone-cylinder models is presented as figure 1. Data obtained in previous tests of a blunt-base parabolic body of revolution (NACA RM-10) are also presented in this report. Information pertaining to the parabolic body is given in references 1 and 2. Each of the three shapes was 50 inches long and all had a fineness ratio of 12.2.

The surface pressure distributions of the three bodies are presented in figure 2. Solid lines indicate that the pressures were derived theoretically and checked experimentally; dashed lines indicate theoretical pressures which were not investigated experimentally. For the ogive-cylinder and cone-cylinder models, the method of characteristics was used to obtain the theoretical pressures. Linear theory was used to determine the pressure distribution over the NACA RM-10 body. The cone-cylinder body had a very strong, favorable pressure gradient at the shoulder; the ogive-cylinder body had a strong, favorable pressure gradient over the first 24 percent of its length, and the parabolic body had a moderate, favorable pressure gradient to about the 78-percent station.

Two different models of the ogive-cylinder shape (designated models 1 and 2 in fig. 1) were tested. Model 1 was used for drag-force measurements and model 2 was used for pressure and boundary-layer measurements. The ogive-cylinder shape (model 2) and the cone-cylinder shape (model 3) were built in five sections and were constructed of an aluminum alloy and steel. The noses of models 2 and 3 were made of steel to minimize sandblasting of the surfaces due to the action of the airstream in the tunnel.

Model 1 was constructed of aluminum alloy and was built in two sections which were joined by means of a $\frac{1}{3}$-turn bayonet screw thread. Iron-constantan thermocouples were imbedded in the surface of model 1 in two axial rows located 180° apart with 15 thermocouples in one row and 5 in the second.

The root-mean-square surface roughness of model 1 (determined by means of a Physicists Research Co. Profilometer, Model No. 11) was 23 ± 5 microinches. The root-mean-square surface roughness of the steel sections of models 2 and 3 was 4 to 6 microinches and the root-mean-square roughness of the aluminum-alloy sections was about 12 microinches. The joints of all models were carefully sealed and were sanded smooth and fair.

The ogive-cylinder and cone-cylinder models were sting mounted. Drag measurements were made on model 1 by means of a single-component internal strain-gage balance system. Base pressures were measured by means of orifices located at two stations inside the model and at different radial positions at the base. Boundary-layer total-pressure profiles were measured by means of a rake located at the bases of models 2 and 3; however, no force measurements were made for these models. Boundary-layer profiles were also determined at various stations on the cylindrical portions of the models ahead of the base, but an analysis of the results showed an increasingly large interference effect between tubes in the survey rake with forward movement; hence, these data are not presented.

TESTS

All tests were conducted at $M = 1.61$ and the models were at zero angle of attack. Measurements were made over a stagnation-pressure range from 2 to 33 pounds per square inch absolute, which gave a Reynolds number range, based on model length, from 2.5×10^6 to 37×10^6. Tunnel stagnation temperature, which was controlled at the lowest practical value consistent with tunnel stagnation pressure, ranged from 100° F to 120° F. Tunnel stagnation dewpoint was kept below -30° F to avoid condensation effects.

The models were tested over the entire Reynolds number range with natural transition and with transition artificially fixed at the nose by No. 60 carborundum grains. All data were obtained at essentially equilibrium surface-temperature conditions. The models were carefully cleaned and checked for minute roughness before each run to eliminate any initial extraneous roughness resulting from sandblasting due to residual dust and particles in the airstream. Sandblasting of the models, especially of model 1, was difficult to avoid, even though particular attention was paid to cleaning the tunnel. Repeated runs and close inspection of the data during each run were necessary to establish the level of the data for essentially smooth conditions.

Simultaneous readings of total drag and base pressure were taken over the entire Reynolds number range for model 1. The forebody pressure-drag coefficient was determined from experimental pressure distributions on an ogive-cylinder model the same as model 1. The experimental pressure distributions were obtained over the ogive at Reynolds numbers, based on a 50-inch length, of 7×10^6, 17.5×10^6, and 28×10^6. There was some increase in forebody pressure-drag coefficient with increasing Reynolds number; however, the change was small in comparison with the scatter of the data and, therefore, has been neglected. A mean value of forebody pressure-drag coefficient of 0.101 was used. The skin-friction coefficients for model 1 were determined by subtracting the sum of this experimental value of pressure-drag coefficient and the measured values of base drag coefficient from the total drag coefficient. Some surface-temperature measurements, with and without transition fixed at the nose of the model, were made for model 1 over the Reynolds number range.

Skin-friction coefficients for models 2 and 3 were obtained from measured boundary-layer total-pressure profiles by means of the loss-in-momentum technique. The method involved the assumptions of a Prandtl number of 1, no heat transfer, and free-stream conditions just outside the boundary layer at the base of the cylinder. Static-pressure measurements indicated that the last-mentioned assumption was justified.

CORRECTIONS AND ACCURACY

No corrections were made for buoyancy effects due to the tunnel pressure gradient, as this effect was found to be negligible. There was some evidence of a slight decrease in test-section Mach number at stagnation pressures less than 4 pounds per square inch absolute; however, estimates showed that no corrections were necessary for this decrease.

The variation of the test-section Mach number ($M = 1.61$) was ±0.01 in the region occupied by the model. There were no significant irregularities in stream flow direction.

The skin-friction coefficients obtained with model 1 are estimated to be accurate within ±0.0001. The corresponding estimated accuracy for models 2 and 3 is ±0.00015.

Model-surface-temperature measurements are estimated to be accurate within $\pm 1.5^{\circ}$ F absolute.

RESULTS AND DISCUSSION

Transition and Skin Friction

The skin-friction results obtained in this investigation are presented in figure 3. Flagged symbols indicate that transition was fixed near the model nose while symbols without flags indicate data obtained with natural transition. The theoretical curves were obtained by the Frankl-Voishel extended method (ref. 3) for the turbulent boundary layer and the Chapman-Rubesin method (ref. 4) for the laminar boundary layer. Mangler's transformation (ref. 5), with the assumption of zero pressure gradient, was used to modify these results and obtain values applicable to the three body shapes investigated. In the case of the turbulent boundary layer, the differences among the three models were so small that a single curve is shown.

The fact that transition is a transient phenomenon is well-known. Because of the damping characteristics of the strain-gage balances and pressure-tube setups used in this investigation, the transition locations discussed in this report are time averaged and not time dependent. However, an analysis of schlieren observation of transition on these and similar bodies and of the skin-friction results of the report indicates that the effect of fluctuations on the skin-friction value at transition is small.

With natural transition, the results indicate an increasing Reynolds number of transition (for transition at the base) as the body shape is changed from a cone-cylinder to an ogive-cylinder to a parabolic body. The estimated values of R_T from figure 3 for these bodies were about 2.5×10^6, 4.7×10^6, and 11×10^6, respectively. These transition Reynolds numbers were checked closely by the values of R_T obtained from an analysis of base-pressure measurements; schlieren flow observations in this and previous investigations have indicated that transition at the body base corresponds to a negative pressure peak in the base-pressure curve. Thus, for transition at the body base, the results show a strong effect on transition due to pressure gradients and also show that it is more desirable to have a long run of moderate, favorable pressure gradient over the whole body with little or no adverse pressure

gradient (as exemplified by NACA RM-10) than a short run of very strong, favorable pressure gradient near the model nose followed by a long run of adverse pressure gradient (as represented by the ogive-cylinder shape). Since the adverse pressure gradients for the ogive-cylinder and cone-cylinder models are similar, the increase in R_T from 2.5×10^6 to 4.7×10^6 indicates the effect of the favorable pressure gradient over the ogive as compared with the neutral gradient over the cone and sharp increase in negative pressure at the juncture of the cone and cylinder.

After transition has occurred at the model base, an increase in Reynolds number (resulting from an increase in the tunnel pressure) causes an increase in skin friction until, at a Reynolds number of about 35×10^6, the skin-friction coefficients are about the same for all models and equal to the turbulent values. In the Reynolds number range from about 16×10^6 to 35×10^6, where transition has moved forward on the body to the regions where the shoulders are located on the cone-cylinder and ogive-cylinder bodies, the skin-friction coefficients for these bodies are less than those for the NACA RM-10 model. This range of lower skin-friction coefficients for the ogive-cylinder and cone-cylinder models may be larger in terms of Reynolds number than is indicated here, because of the possibility that the rather abrupt increase in C_f for the ogive-cylinder models near $R = 30 \times 10^6$ may be partly due to sand-blast effects which could not be entirely eliminated in a small number of test runs. Since transition is close to the shoulder on the ogive-cylinder and cone-cylinder models within this Reynolds number range, the lengths of adverse pressure gradient involved become small and the effect of the adverse pressure gradients can be largely discounted. Therefore, it may be concluded that, on the basis of a comparison of the results for the various bodies within this Reynolds number range, for equal lengths of favorable pressure gradient from the nose of the model, the strongest, favorable pressure gradient will produce the largest Reynolds number of transition. This result is, of course, in agreement with previous observations at subsonic speeds.

It is interesting to note the apparently strong effect on boundary-layer stability of the flow expansion or acceleration about the sharp shoulder of the cone-cylinder model. This effect is deduced from the fact that, within the Reynolds number range from 16×10^6 to 35×10^6, the skin-friction coefficient for the cone-cylinder body is less than that for the NACA RM-10 body (compare pressure results only) which has a favorable pressure gradient.

No reliable general conclusion can be made regarding the agreement between theoretical and experimental skin-friction values for the cone-cylinder and ogive-cylinder models when the boundary layer is laminar over the entire model, because of the sparsity of data in this region. The theoretical and experimental results for the NACA RM-10 body, however, are in good agreement.

When transition is fixed near the nose, the force-test results for the ogive-cylinder and NACA RM-10 models are in good agreement with one another and with theory. The skin-friction results obtained from boundary-layer surveys for the cone-cylinder and ogive-cylinder models also agree with one another and with the high Reynolds number pressure-survey data for the NACA RM-10 model which has natural transition. The survey data, however, generally fall about 15 percent below the force-test results. This discrepancy between pressure- and force-test results also occurs with natural transition and is due largely to mutual interference between the closely spaced tubes in the survey rake. A part of the discrepancy may also result from nonuniform boundary-layer thickness around the base of the model. From a comparison of all fixed-transition data, body shape or pressure gradients appear to have little or no effect on the average skin-friction coefficients for a turbulent boundary layer for bodies of high fineness ratio.

Surface-Temperature Surveys

The results of the surface-temperature surveys made on the 25-microinch ogive-cylinder model are given in figure 4. These surveys were undertaken to determine the possibility of following the forward movement of transition on the model which resulted from an increase in Reynolds number.

The results in figure 4 show an average ratio of surface temperature to stagnation temperature $\frac{T_e}{T_o}$ of about 0.95 at the lowest test Reynolds number for natural transition. As the Reynolds number is increased, the temperature ratio at the base of the model begins to increase to a value slightly greater than 0.96, the value measured for the turbulent boundary layer with fixed transition, and the temperature rise begins to move forward on the model. Because of the gradual increase in surface temperature and the effects of local-velocity changes in the vicinity of the ogive-cylinder shoulder, the transition location could not be determined with any accuracy. In an attempt to eliminate the effects of local velocity, some of the data were reduced to temperature recovery factors as shown in figure 5. Again, accurate tracing of the movement of transition was not feasible. This difficulty stemmed primarily from the large skin thickness of the model (the model was not designed with such tests in mind) and the relatively large change in local velocities on the forward part of the model. The average surface-temperature recovery factors of approximately 0.86 for laminar flow and 0.89 for the turbulent boundary layer are in good agreement with experimental recovery factors determined in other investigations in the same speed range and with the square root and cube root of the Prandtl number, respectively, when the Prandtl number is taken as 0.73.

Correlation of Pressure-Gradient Effects

For two-dimensional flow with constant pressure gradient, theoretical considerations indicate the possibility of correlating the transition results for different pressure gradients on the basis of a parameter involving the boundary-layer momentum thickness and pressure gradient at the point of transition. An attempt to correlate the transition results for the three bodies investigated on this basis was not successful. The study indicated that, for three-dimensional bodies which have both favorable and unfavorable pressure gradients, it was unlikely that a correlation could be obtained on any basis that did not consider intimately the flow conditions over the whole length of the model.

SUMMARY OF RESULTS

An exploratory investigation has been made in the Langley 4- by 4-foot supersonic pressure tunnel at a Mach number of 1.61 to determine the skin friction and boundary-layer transition on three bodies of revolution having different shapes and pressure distributions. The results may be summarized as follows:

1. The effects of pressure gradient on boundary-layer transition were qualitatively the same as those commonly observed at subsonic speeds.

2. For transition at the body base, the highest transition Reynolds numbers were obtained with a long run of moderate, favorable pressure gradient followed by little or no adverse pressure gradient (NACA RM-10 parabolic body) rather than with a short run of very strong, favorable pressure gradient near the model nose followed by a long run of adverse pressure gradient.

3. When transition occurred on the forward part of the body near the downstream end of the region of favorable pressure gradient, the transition Reynolds number was highest for the ogive-cylinder and cone-cylinder bodies which had the strongest favorable pressure gradients.

4. Body shape or pressure gradients had little or no effect on the average skin-friction coefficients of the bodies investigated, when the boundary layers were entirely turbulent.

5. The average surface-temperature recovery factors of approximately 0.86 for laminar flow and 0.89 for the turbulent boundary layer are in

good agreement with experimental recovery factors determined in other investigations in the same speed range and with the square root and cube root of the Prandtl number, respectively, when the Prandtl number is taken as 0.73.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 15, 1954.

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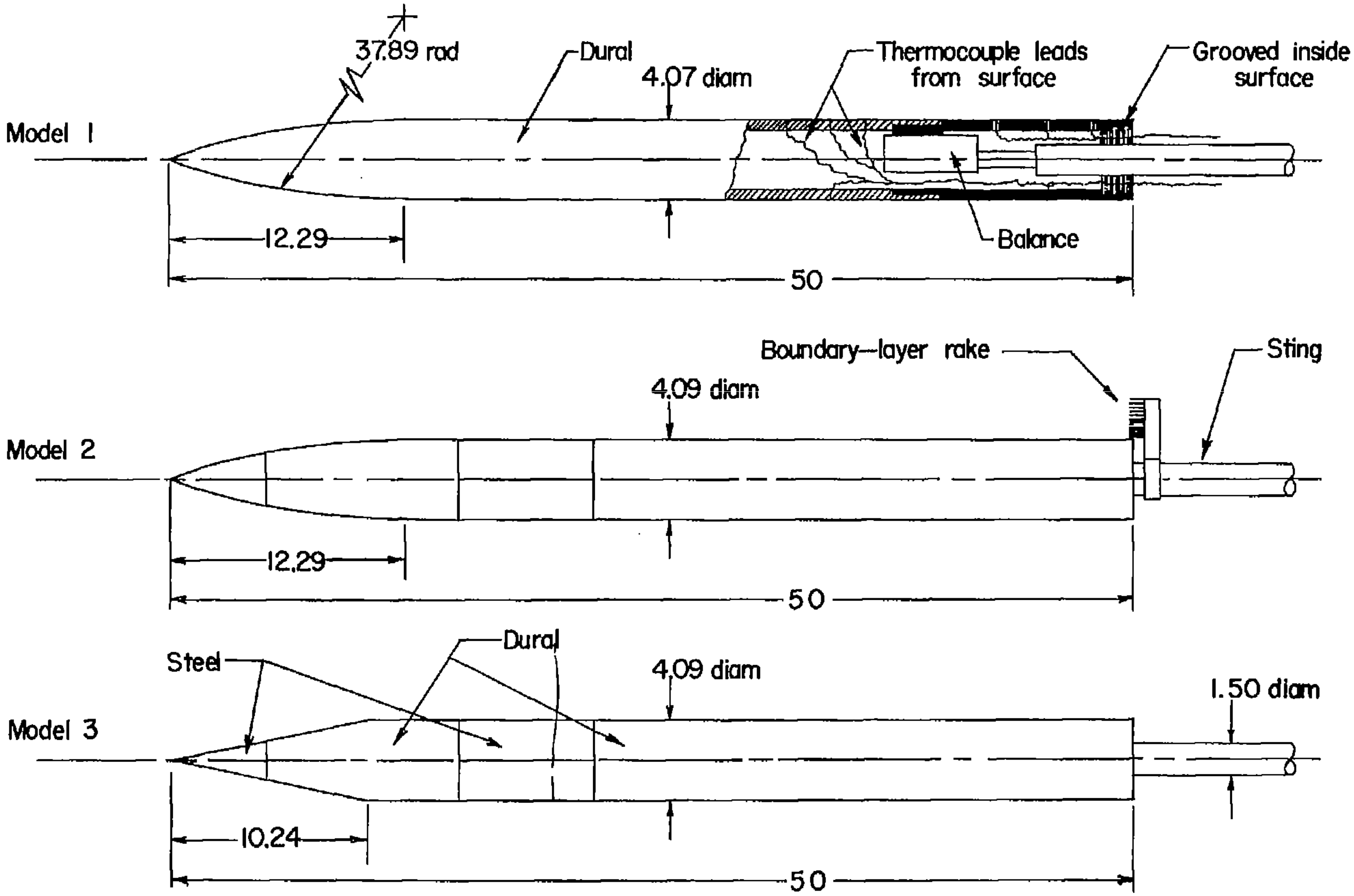


Figure 1.- Schematic drawing of test models. All dimensions are in inches.

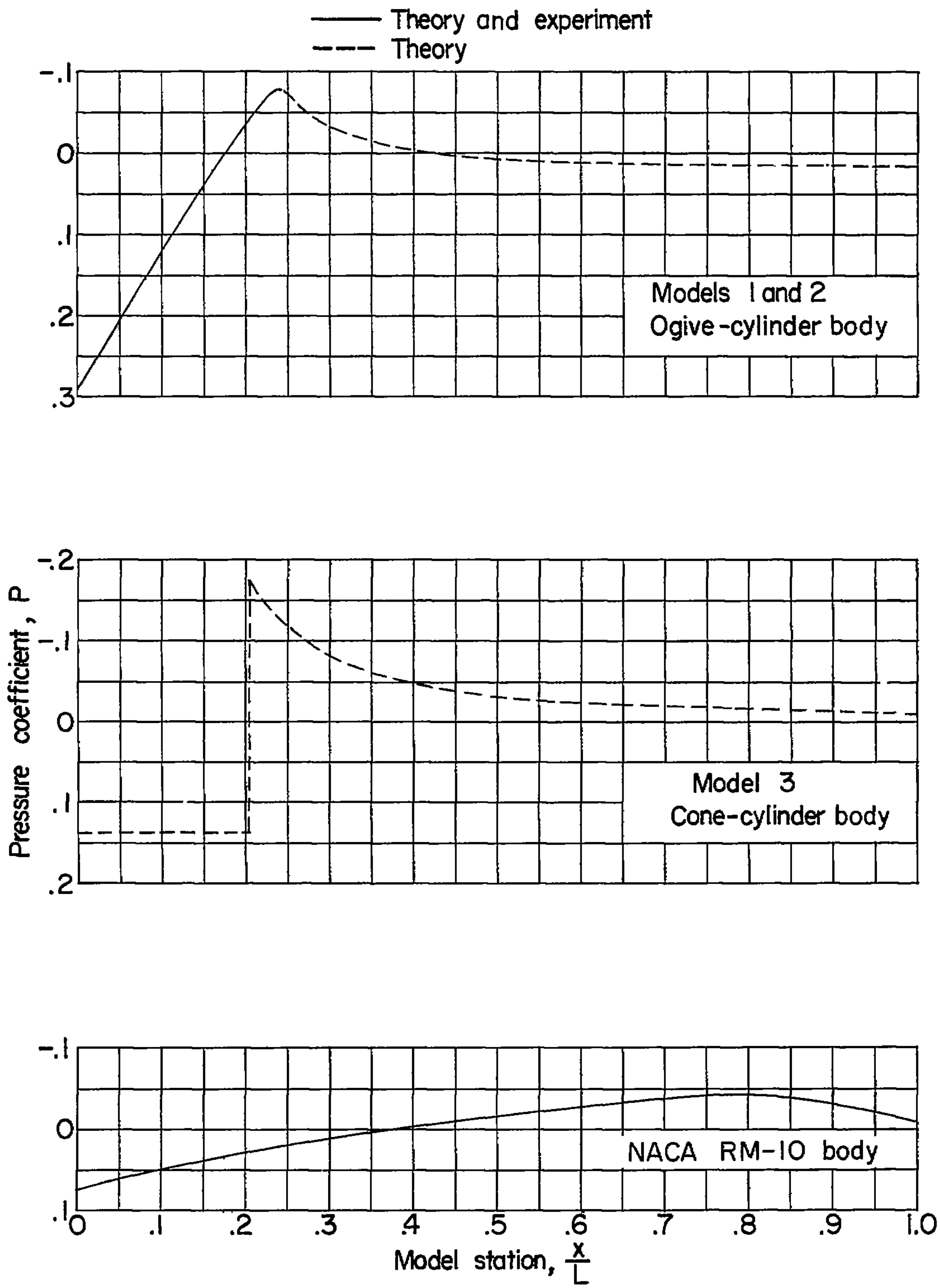


Figure 2.- Pressure distributions for three bodies of revolution.
$M = 1.61$; $\alpha = 0^{\circ}$.

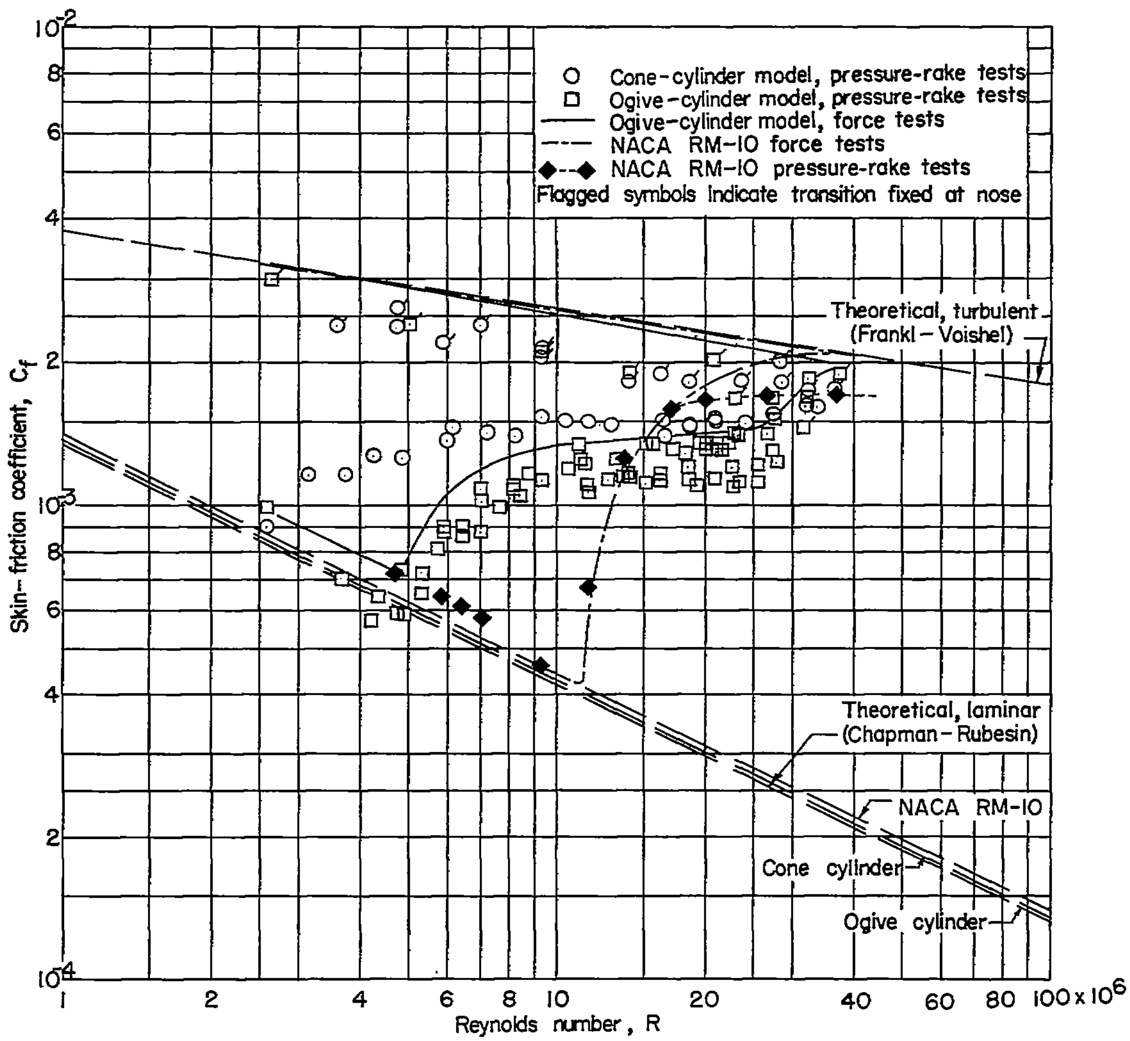
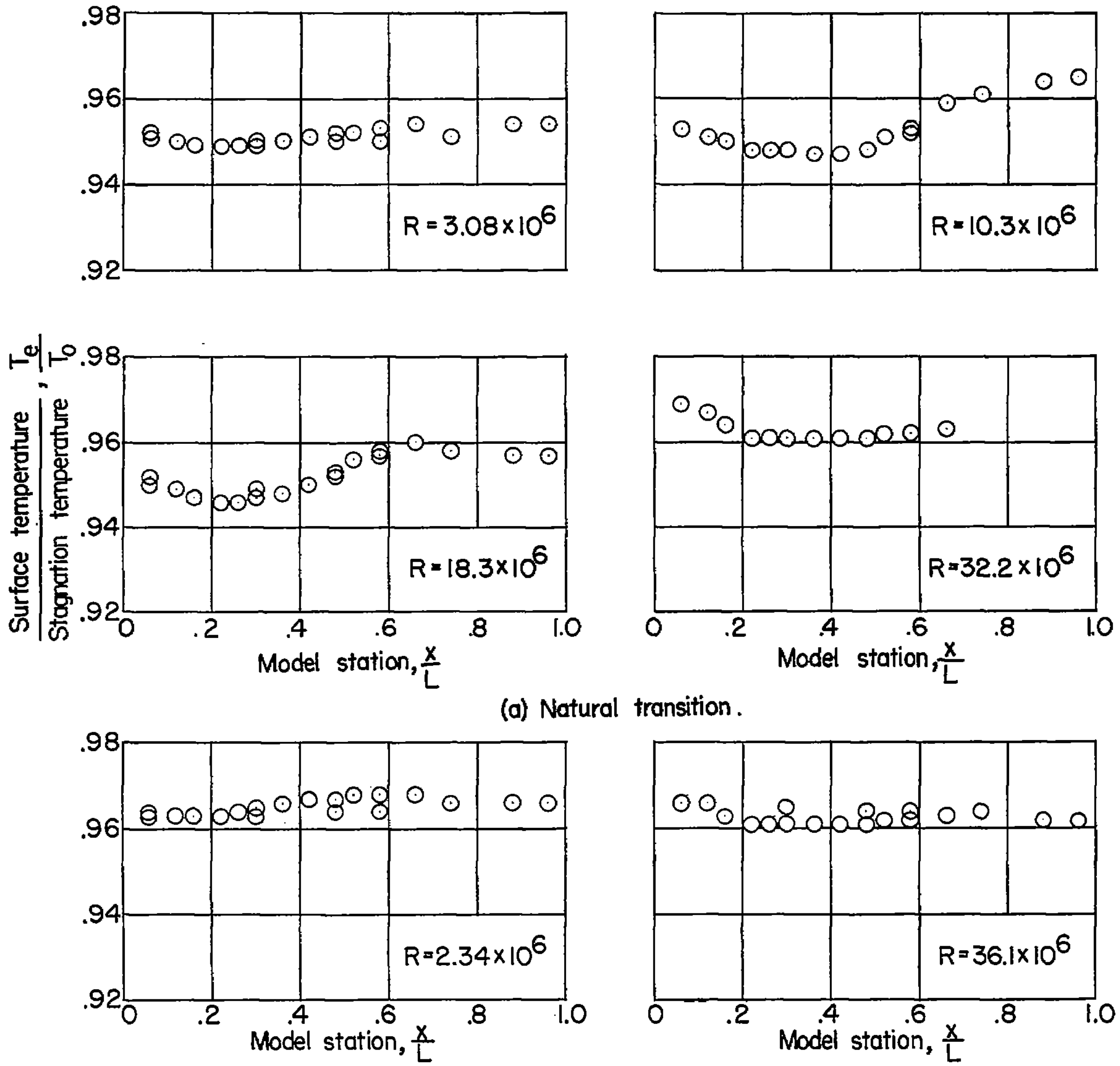


Figure 3.- Variation of skin-friction coefficients with Reynolds number for different bodies of revolution. $M = 1.61$; $\alpha = 0^\circ$.



(a) Natural transition.

(b) Fixed transition.

Figure 4.- Temperature-distribution measurements along surface of a 25-microinch ogive-cylinder model at different Reynolds numbers. M = 1.61.

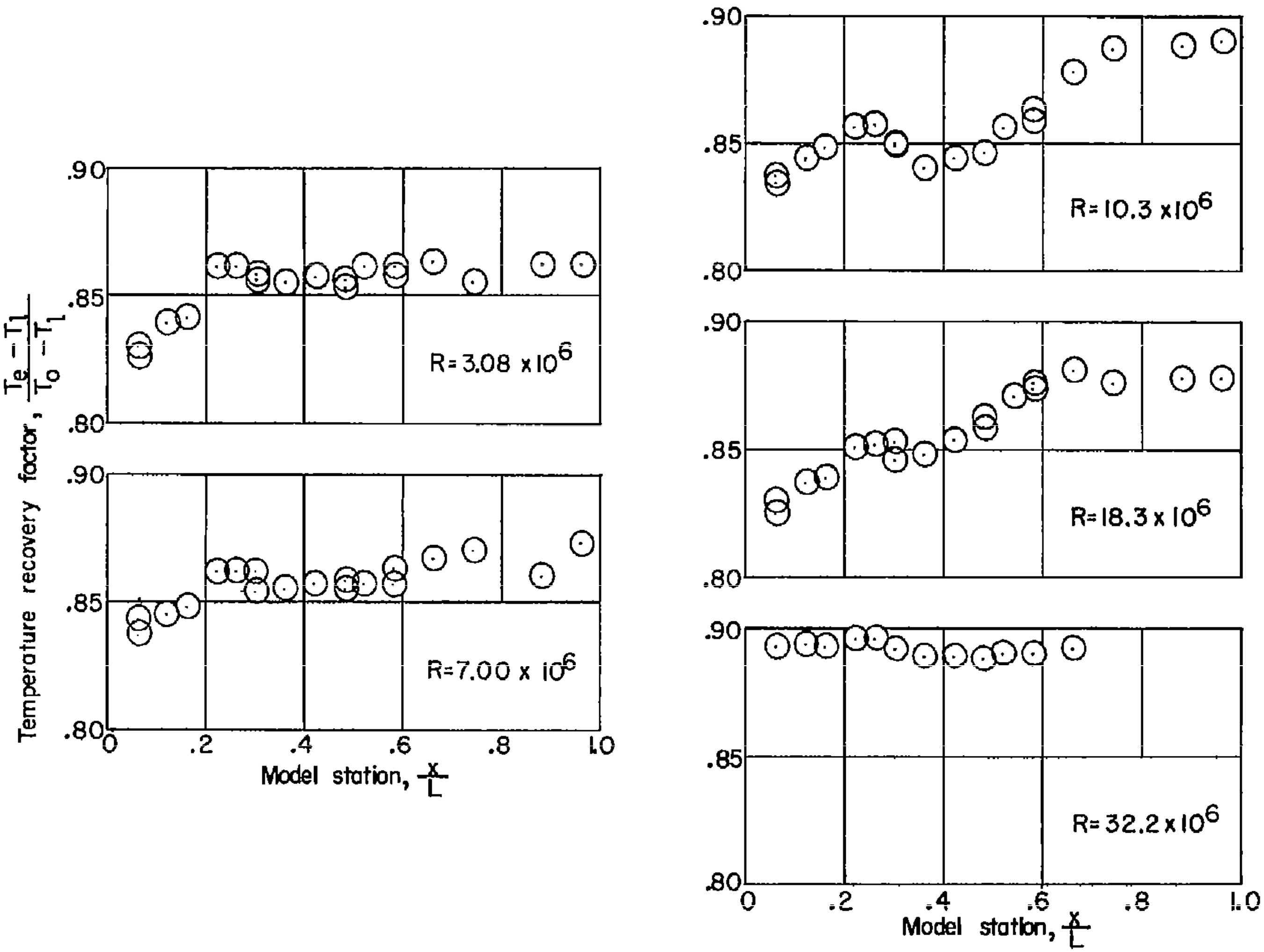


Figure 5.- Temperature-recovery-factor distributions along surface of a 25-microinch ogive-cylinder model at different Reynolds numbers. $M = 1.61$.

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